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TRANSMISSION AND BACKSCATTER COEFFICIENTS OF 1.0- TO 3.0-MeV ELECTRONS INCIDENT ON SOME METALS AND ALLOYS

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16. Abstract

The transmission and backscatter coefficients of aluminum, titanium, vanadium, copper, gold, and the alloys Ti-6Al-4V and 50 percent copper – 50 percent gold were determined experimentally for normally incident electrons of 1.0 to 3.0 MeV. From the transmission measurements, the extrapolated range of electrons as a function of energy was determined for each material. Analysis showed that the extrapolated range and maximum backscatter of electrons in an alloy can be calculated to within a few percent from the range and backscatter of electrons in the constituent elements.

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TRANSMISSION AND BACKSCATTER COEFFICIENTS OF 1.0- TO 3.0-MeV ELECTRONS INCIDENT ON SOME METALS AND ALLOYS

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SUMMARY

Results of an experimental study of the transmission and backscatter coefficients for aluminum, titanium, vanadium, copper, gold, and the alloys Ti-6Al-4V and 50 percent copper – 50 percent gold irradiated with 1.0- to 3.0-MeV electrons are reported. From transmission measurements, the extrapolated range of electrons as a function of energy was determined for each material. Transmission measurements showed that more electrons are ejected from very thin targets than are stopped within the targets. In addition, the maximum backscatter of electrons was determined for each material as a function of incident energy. Analysis showed that the extrapolated range and maximum backscatter of electrons in an alloy can be calculated to within a few percent from the range and backscatter of electrons in the constituent materials.

INTRODUCTION

The radiation belts surrounding the earth pose a hazard to many satellite components that is sufficient to require radiation shielding. Since energetic electrons are a major constituent of the radiation belts (refs. 1 and 2), shielding against them is of prime importance.

Because of the essentially random manner in which electrons lose their energy, current theoretical treatments of their energy loss are not totally satisfactory. Therefore, as a means of providing maximum shielding effectiveness with minimum weight penalty, experimental measurements are necessary to obtain the transmission and backscatter coefficients for different materials subjected to energetic electrons. The present investigation was undertaken to determine the transmission and backscatter coefficients for aluminum, titanium, vanadium, copper, gold, and the alloys Ti-6Al-4V and 50 percent Cu – 50 percent Au. These materials were chosen because of their wide use in space engineering applications. The extrapolated ranges of the incident electrons in the

target materials were also determined, and values for the alloys were related to those for the constituent elements by a simple weighted atomic percentage relationship.

The objectives of the experiment were accomplished by subjecting the target materials to energetic electrons with energies of 1.0, 1.5, 2.0, 2.5, and 3.0 MeV. All tests were conducted in a vacuum at room temperature with the targets perpendicular to the electron beam. The parameters which were varied were the target thickness, target material, and the electron beam energy. The transmission and backscatter coefficients for each material were determined for a number of target thicknesses up to, and slightly beyond, the extrapolated range of the material.

APPARATUS AND TESTS

Accelerator

The metallic targets were irradiated with electrons from a 3.0-MeV Van de Graaff generator. The overall experimental arrangement is shown in figure 1. The electrons were directed to the center of the analyzing magnet by the X-Y steering mechanism of the Van de Graaff generator. The analyzing magnet current was adjusted to direct the electron beam to the scattering chamber, where the irradiations took place.

The electron beam was focused and collimated to the desired spot size by the quadrupole magnets and collimator sections, as indicated in figure 1. The electron beam energy was measured through 2.5 MeV by use of a 5-mm silicon solid-state detector. These measurements were accurate to within the resolution of the detector, which was approximately 20 keV (full width at half maximum). For the 3.0-MeV electrons a calibrated generating voltmeter, which was also accurate to within 20 keV, was used.

Experimental Procedure

After positioning and collimating, the electron beam was introduced into the scattering chamber shown in figure 2. Inside the main scattering chamber was located a second chamber, a half-cylinder concentric with the main scattering chamber. The half-cylinder contained a 1.27-cm-diameter aperture on its near side to permit the electron beam to enter. The 1.27-cm-diameter hole occupied approximately 0.23 percent of the total area of the half-cylinder and thus was not a significant fraction of the area of the half-cylinder. In addition, the beam backscattered from a metallic target is not scattered isotropically but follows an angular distribution peaked at about 30° to 40° (ref. 3). Another opening (approximately 1.9 cm high by 3.8 cm wide) was located on the flat side of the half-cylinder to permit placement of the target. The insides of both the half-cylinder and the main scattering chamber were lined with carbon to reduce the number of secondary scattering events.

The main scattering chamber was used to monitor the transmission of the electrons through the target materials, and the half-cylinder was used to monitor the backscatter of electrons from the target materials. An aluminum baffle, electrically connected to the carbon liner on the inside of the main scattering chamber, served as a shield to collect any electrons scattered by its liner. The half-cylinder, the scattering chamber, and the target were electrically insulated from each other so that independent current measurements could be made.

With a target in place and the electron beam turned on the target, the signals from the transmission, target, and backscatter collectors were fed into integrating electrometers. The integrating electrometers were arranged so that absolute measurements could be made of the electrons transmitted, backscattered, and absorbed by the target. Furthermore, they were connected to an electronic switch so that they could be started and stopped in unison.

The geometry of the system was arranged so that electrons passing through the 0.63-cm-diameter beam-entrance aperture could not strike the backscatter chamber. When test runs were made on the system without a target in position, the current measured by the backscatter chamber was approximately 0.1 percent of the total beam. All tests were conducted in a vacuum of 1 to 2×10^{-6} mm Hg, at room temperature, and with the samples normal to the electron beam.

Test Samples

The test samples were foils of aluminum, titanium, vanadium, copper, gold, and the alloys Ti-6Al-4V and 50 percent Cu – 50 percent Au. The elemental samples were of high purity (at least 99.99 percent pure). The alloy samples were not made to any specific degree of purity. All samples were selected from materials that were free of scratches, pits, and voids.

The thickness of the test samples ranged from 1 to 240 mils (0.0025 to 0.61 cm). For the thick targets it was necessary to stack together some of the thinner samples; however, reference 4 has shown that this procedure has no effect on the transmission or backscatter coefficients. The main parameter of interest was the "thickness" of a sample in units of mg/cm^2, determined by dividing the mass of a sample by its area.

Before irradiation, each sample was cut into a rectangle with the dimensions of 2.54 cm by 6.35 cm. The sample was then inspected, cleaned, and mounted in a frame for irradiation.

Errors

Target size.- The width and length of the target were measured to within about 0.025 cm and weighed to an accuracy of 1 milligram. Measurements of sample thickness made with a micrometer indicated uniformity to within about ±1 percent.

Beam energy.- The maximum error in beam energy could be as high as 2 percent for 1.0-MeV electrons, and less than 1 percent for 3.0-MeV electrons. Errors of this magnitude would have a negligible effect on the transmission and backscatter coefficients. This can be shown by examining the change of the maximum backscatter coefficients with electron energy. For example, from the data presented herein (fig. 18), the change for aluminum was 0.04-percent change in backscatter for a 20-keV change in electron energy.

Integrated current measurements.- Because the entire electron beam was made to impinge on the target, integration of the current is the only source of systematic measurement error. Precisely known currents (less than 1-percent error) were used to calibrate the integrating electrometers, and the calibrations were accurate to better than 1 percent.

Other sources of error.- An analysis was made of the errors that could result from the following sources:

(a) Backscatter from the transmission monitor to the target

(b) Backscatter from the target through the 1.27-cm-diameter aperture in the backscatter monitor

(c) Twice backscattered electrons from the backscatter monitor to the target

(d) Electrons scattered from the 0.63-cm-diameter beam entrance aperture to the backscatter monitor

The total from all these errors would be less than 1 percent.

Summary of errors.- In summary, the transmission and backscatter measurements are accurate to within less than 2 percent.

RESULTS AND DISCUSSION

Transmission

The results of the transmission measurements for aluminum, Ti-6Al-4V, titanium, vanadium, copper, 50 percent Cu – 50 percent Au, and gold are shown in figures 3 to 9. For each target material there is a family of curves for electrons incident at energies of 1.0, 1.5, 2.0, 2.5, and 3.0 MeV. As expected, for each material the transmission coefficients increase with electron energy for a given target thickness. On the other hand, the

transmission coefficients decrease with increasing effective atomic number Z of the target material. For example, 1.0-MeV electrons incident on a thickness of aluminum equal to 200 mg/cm^2 yield a transmission coefficient of approximately 73 percent (fig. 3), whereas 1.0-MeV electrons incident on a thickness of gold equal to 200 mg/cm^2 yield a transmission coefficient of approximately 20 percent (fig. 9). The primary reason for the smaller transmission coefficient for materials of high Z is that, on the average, the angular deflections of the electrons during interactions or collisions with such materials are greater than the angular deflections of electrons interacting with materials of low Z (ref. 3). The collisions at larger angular deflections lead to an increase in pathlength for the electrons; thus, while the straight-through distance for a material of high Z will be less than for a material of low Z, for equal amounts in mg/cm^2, the actual pathlength will be greater for the material of high Z. This combination of greater angular deflections per collision and greater actual pathlength for targets of high Z leads to an increase in the backscatter of electrons from the target and, to a lesser extent, an increased absorption within the target and thus causes the transmission coefficients to be smaller.

Further examination of the transmission curves reveals a part in which, when the target thickness is small, the transmission is apparently greater than 100 percent. This phenomenon was detected during the experiments by measuring a positive current on the targets during irradiation, which indicated that more electrons were leaving the target than were entering the target. This condition arises when the quantity of secondary electrons escaping from the target is greater than the number of primary electrons stopped within the target. For purpose of clarity, the data points were omitted from the part of the curves where the transmission was greater than 100 percent and the curves are shown as solid lines. It is emphasized that these parts of the curves are fitted to data and do not represent extrapolations or trends.

As the target thickness is increased, the transmission coefficients decrease linearly until they reach a value between 20 and 30 percent. From this region on, the addition of more target material yields only a small decrease in the transmission coefficients. It is in this region that range-energy straggling is predominant (ref. 5).

If the linear portion of the transmission plots is extended to the point where they cross the abscissa of the figures, the extrapolated range of electrons in the various materials can be determined as a function of the incident electron energy. This determination is accomplished by applying a least-squares fit to the experimentally determined transmission coefficients between approximately 70 and 30 percent relative transmission to obtain a straight line which is then extrapolated to zero percent transmission. The results are shown in table I. Since the transmission coefficients decreased as the atomic number of the target material increased, it would be expected that the extrapolated ranges

would follow the same trend. Examination of table I shows that this is the case. The extrapolated ranges for the higher atomic number materials, gold and copper, are substantially less than the ranges for the lower atomic number materials, aluminum and titanium.

The results obtained for aluminum were compared with those calculated from an empirical relationship (ref. 5):

$$R_o = 530E - 106$$

where R_o is the extrapolated range in mg/cm^2 and E is the incident electron energy in MeV. This empirical relationship, which has an accuracy of ±5 percent, was derived from the results of a number of independent investigations of electrons incident on aluminum. The results of a comparison between present experimental results and the empirical relationship from reference 5 is shown in table II and indicate agreement to well within the accuracy of the equation.

The transmission coefficients for 1.0-MeV electrons normally incident on aluminum were also compared with those calculated by Berger and Seltzer (ref. 6) and Perkins (ref. 7). Results of this comparison are shown in figure 10. For purposes of comparison, the abscissa of the calculated transmission coefficients was converted to mg/cm^2. The data in figure 10 indicate that the results from this investigation agree with the Monte Carlo calculations of Berger and Seltzer to within approximately 2 or 3 percent except when the targets are very thick. For the results of Perkins (ref. 7), the agreement is very good when the targets are thin, 75 to 175 mg/cm^2; however, from this point on, the agreement steadily becomes less, approaching 30 to 40 percent as the targets become very thick.

For the materials other than aluminum, almost no experimental data exist that could be compared with the results of this investigation. As a consequence, it was assumed that the transmission coefficients and extrapolated range measurements for titanium, vanadium, Ti-6Al-4V, copper, gold, and the alloy 50 percent Cu – 50 percent Au had the same degree of accuracy as the measurements for aluminum.

A method was found to compute the extrapolated range of electrons in an alloy by knowledge of the extrapolated range in the constituent materials. The method involves first finding the atomic fraction of each alloy constituent and the normalizing to a $Z^2 + Z$ dependence to take into account the increased scattering as the atomic number increases (ref. 5). When this method was used, the normalized atomic fractions found for Ti-6Al-4V were Ti = 0.919, Al = 0.039, and V = 0.042; for the alloy 50 percent Cu – 50 percent Au, the values were Cu = 0.298 and Au = 0.702. The extrapolated range of an alloy constituent is then multiplied by the normalized atomic fraction for that constituent. The procedure is repeated for all constituents of the alloy, and the resultants are summed

to give the computed extrapolated range. For example, the computed extrapolated range for 1.0-MeV electrons incident on 50 percent Cu – 50 percent Au would be $(0.298 \times 348\ \text{mg/cm}^2) + (0.702 \times 247\ \text{mg/cm}^2) = 277\ \text{mg/cm}^2$. The values obtained for the extrapolated ranges computed by this method are shown in table III. For purposes of comparison, the experimental extrapolated ranges for the alloys are also presented. For the Ti-6Al-4V alloy the deviation between the experimental and computed values of the extrapolated range varied from zero at 2.5 MeV to a high of 3.0 percent at 1.5 MeV. For the alloy 50 percent Cu – 50 percent Au, the deviation varied from a low of 1.5 percent at 1.0 MeV to a high of 6.0 percent at 2.5 MeV with an average deviation of 3.0 percent.

Backscatter

The results of the backscatter measurements are shown for aluminum, alloy Ti-6Al-4V, titanium, vanadium, copper, alloy 50 percent Cu – 50 percent Au, and gold in figures 11 to 17. For each target material, the backscatter coefficients increase with decreasing energy. This result arises because of the condition that in electron-nucleus collisions the lower-energy electrons are scattered at a sharper angle and are turned in a backward direction at a greater rate than the higher-energy electrons. When the targets are thin, the backscatter curves are characterized by small values of backscatter. Addition of more target material causes a small increase in the amount of backscatter until a point is reached where the backscatter increases almost linearly with the addition of more material. The rate of increase then tapers off and finally ceases at some level, known as the maximum backscatter, which is characteristic of the target material, the energy of the incident electrons, and the angle of the beam incidence.

Figure 18, which shows the maximum backscatter for each material as a function of incident electron energy, clearly indicates that the maximum backscatter increases with increasing atomic number. For example, the values for 1.0-MeV electrons vary from a low of 9 percent for aluminum to a high of 46.5 percent for gold; and the values for 3.0-MeV electrons vary from a low of 4.6 percent for aluminum to a high of almost 34 percent for gold. This result is due to the fact that for a given energy loss the angular deflection increases with increasing atomic number (ref. 3).

Figure 18 also compares the results of this investigation with results obtained by other investigators. The experimental results of Cohen and Koral (ref. 8) at electron energies of 1.0 MeV and 1.8 MeV are shown for aluminum and gold. For aluminum, the results agree to within 6 percent at 1.8 MeV; for gold the results agree to within about 2 percent. For 2.0-MeV electrons, the results of Wright and Trump (ref. 9) are compared with the present results for aluminum, copper, and gold. As can be seen, the agreement is within approximately 5 percent for the gold; for copper and aluminum, the results agree

almost exactly. The results of Monte Carlo calculations based on 1000 histories by Berger (ref. 3) for the maximum backscatter of 1.0-MeV and 2.0-MeV electrons incident on aluminum are also shown in figure 18. At 1.0 MeV, the results are identical; at 2.0 MeV, the results differ by approximately 8.0 percent.

This relatively good agreement of the aluminum, copper, and gold data with results of other experiments and calculations justifies a high degree of confidence in the data for the other materials for which no direct comparisons are available.

It is possible to calculate the maximum backscatter for an alloy material from knowledge of the maximum backscatter for the constituent elements. The procedure is identical to the one previously outlined for finding the extrapolated range of alloys. Table IV gives the results of this calculation for the two alloys investigated. For purposes of comparison, the experimental values are also presented. The deviation for the Ti-6Al-4V alloy varied from a low of 0.94 percent at 3.0 MeV to a high of 7.28 percent at 1.5 MeV with an average agreement of 3.59 percent. For the alloy 50 percent Cu – 50 percent Au, the deviation varied from a low of 7.34 percent at 1.0 MeV to a high of 9.84 percent at 3.0 MeV with an average agreement of 8.92 percent.

CONCLUSIONS

Transmission and backscatter coefficients were measured, and the extrapolated range was calculated for electrons normally incident, in the energy range 1.0 MeV to 3.0 MeV, on aluminum, titanium, vanadium, copper, gold, and alloys Ti-6Al-4V and 50 percent copper – 50 percent gold.

1. The experimental transmission coefficients for electrons incident at 1.0 MeV on aluminum showed agreement to within 2 or 3 percent of previous Monte Carlo electron transmission calculations by Berger and Seltzer (NASA SP-71).

2. The extrapolated range measurements for aluminum agreed to within 0.4 percent with a previously developed empirical equation.

3. When the targets are very thin, more electrons are ejected from the target material than are stopped within the target material. This resulted in transmission coefficients that were apparently greater than 100 percent.

4. Experimentally determined maximum backscatter coefficients agree with results of other available data from experiments and calculations, with the results showing agreement to within 8 percent.

5. It is possible to calculate the extrapolated range and the maximum backscatter of electrons incident on an alloy within a few percent from known values of the extrapolated range or maximum backscatter of electrons incident on the constituent elements.

Langley Research Center
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 12, 1970.

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TABLE I.- EXPERIMENTAL EXTRAPOLATED RANGE MEASUREMENTS

Material	Energy, MeV	Experimental extrapolated range, mg/cm^2
Aluminum Z = 13	1.0	424 ± 8
	1.5	692 ± 14
	2.0	951 ± 19
	2.5	1219 ± 24
	3.0	1487 ± 30
Ti-6Al-4V Z = 21.5	1.0	365 ± 7
	1.5	617 ± 12
	2.0	867 ± 17
	2.5	1103 ± 22
	3.0	1386 ± 28
Titanium Z = 22	1.0	364 ± 7
	1.5	594 ± 12
	2.0	858 ± 17
	2.5	1097 ± 22
	3.0	1342 ± 27
Vanadium Z = 23	1.0	365 ± 7
	1.5	617 ± 12
	2.0	814 ± 16
	2.5	1137 ± 23
	3.0	1341 ± 27
Copper Z = 29	1.0	348 ± 7
	1.5	586 ± 12
	2.0	779 ± 16
	2.5	1069 ± 21
	3.0	1299 ± 26
50% Cu – 50% Au Z = 54	1.0	273 ± 5
	1.5	451 ± 9
	2.0	642 ± 13
	2.5	799 ± 16
	3.0	1053 ± 21
Gold Z = 79	1.0	247 ± 5
	1.5	373 ± 7
	2.0	563 ± 11
	2.5	754 ± 15
	3.0	922 ± 18

TABLE II.- COMPARISON OF EXPERIMENTAL AND CALCULATED EXTRAPOLATED RANGES FOR ALUMINUM

Energy, MeV	Extrapolated range, mg/cm^2	
	Experimental	Empirical (a)
1.0	424	424
1.5	692	689
2.0	951	954
2.5	1219	1219
3.0	1487	1484

[a] $R_o = 530E - 106$ (ref. 5).

TABLE III.- COMPARISON OF EXPERIMENTAL AND CALCULATED EXTRAPOLATED RANGES FOR Ti-6Al-4V AND 50% Cu – 50% Au

Energy, MeV	Extrapolated range, mg/cm^2		Deviation, percent
	Experimental	Calculated	
	Ti-6Al-4V		
1.0	365	366	0.27
1.5	617	599	3.01
2.0	867	859	.93
2.5	1103	1103	.00
3.0	1386	1348	2.82
	50% Cu – 50% Au		
1.0	273	277	1.47
1.5	451	436	3.44
2.0	642	627	2.39
2.5	799	847	6.01
3.0	1053	1034	1.84

TABLE IV.- COMPARISON OF EXPERIMENTAL AND CALCULATED MAXIMUM BACKSCATTER COEFFICIENTS FOR Ti-6Al-4V AND 50% Cu – 50% Au

Energy, MeV	Maximum backscatter, percent		Deviation, percent
	Experimental	Calculated	
Ti-6Al-4V			
1.0	18.0	18.3	1.67
1.5	15.1	16.2	7.28
2.0	13.2	13.7	3.79
2.5	11.7	12.2	4.27
3.0	10.6	10.7	.94
50% Cu – 50% Au			
1.0	36.8	39.5	7.34
1.5	33.5	36.6	9.25
2.0	30.5	33.1	8.52
2.5	28.0	30.7	9.64
3.0	25.5	27.9	9.84

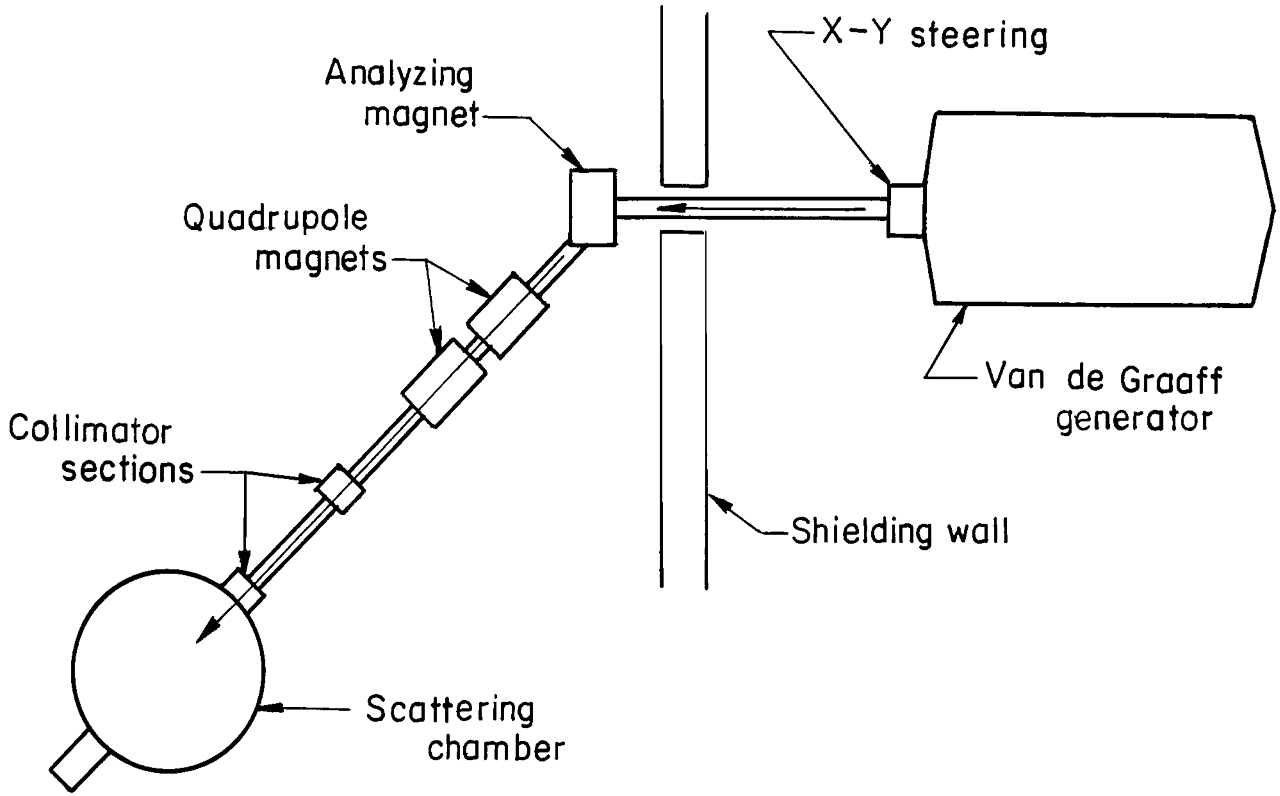

Figure 1.- Overall experimental arrangement.

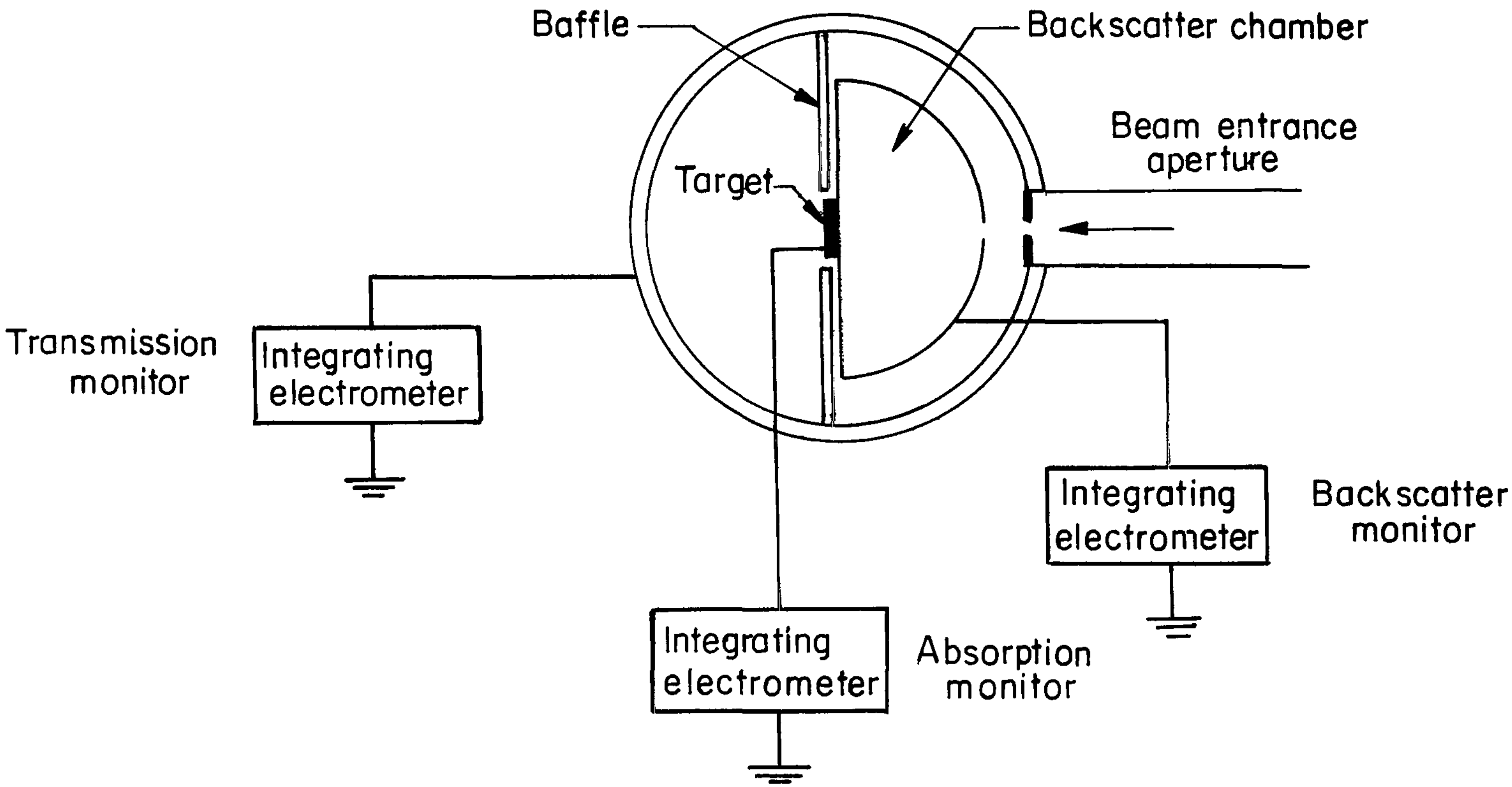

Figure 2.- Scattering chamber used for making transmission and backscatter measurements.

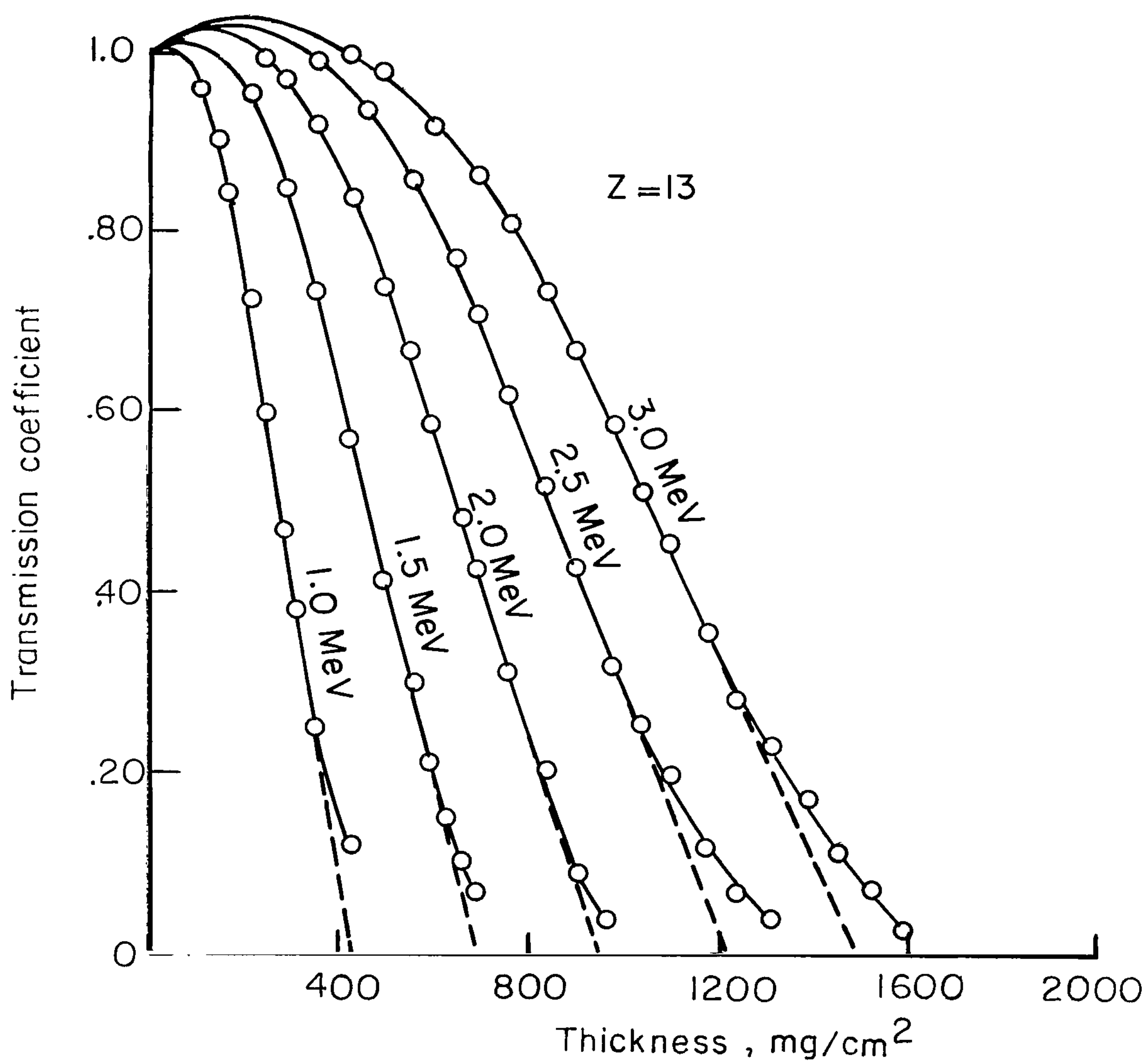

Figure 3.- Transmission coefficients as a function of target thickness for electrons normally incident on aluminum.

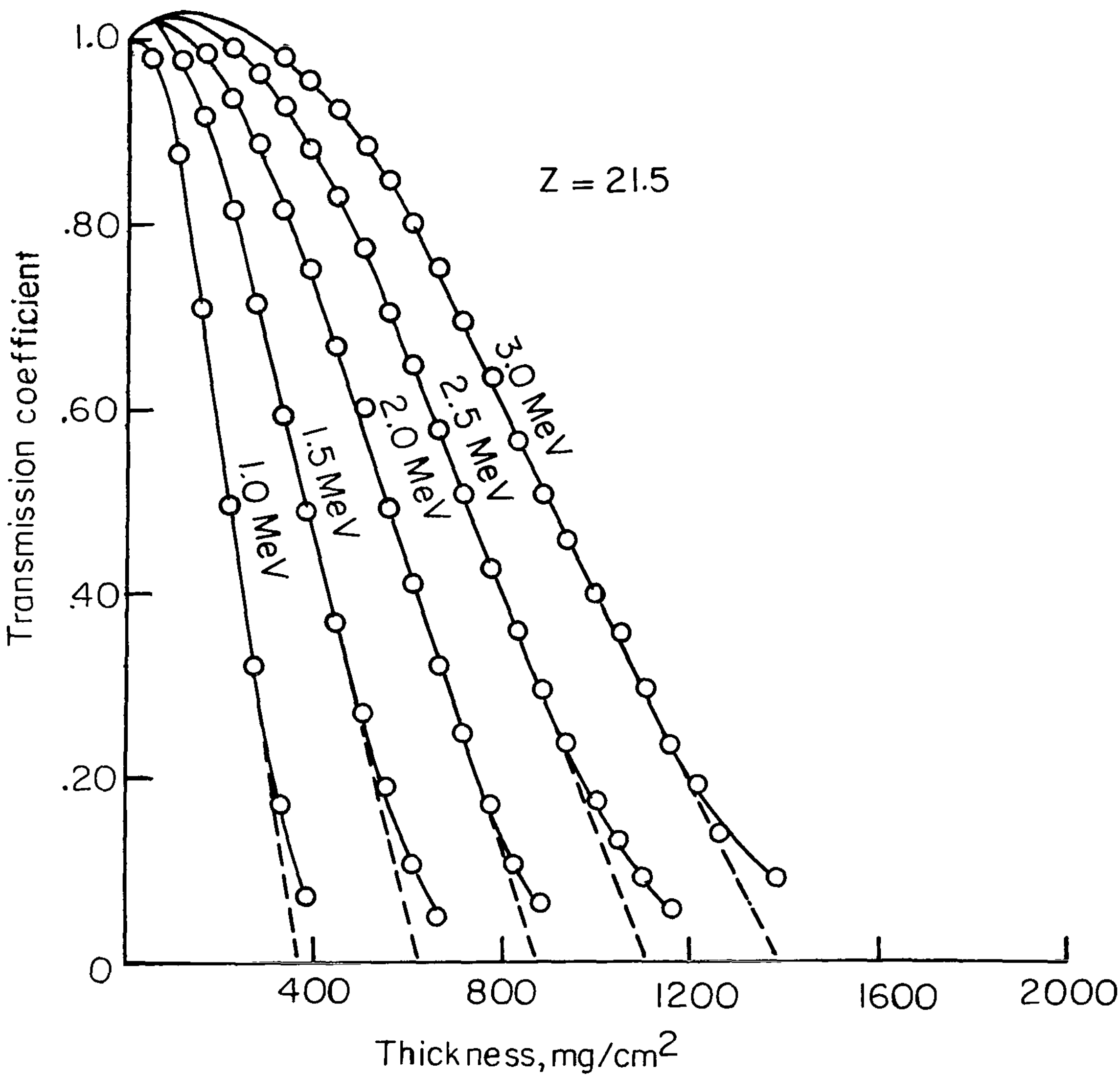

Figure 4.- Transmission coefficients as a function of target thickness for electrons normally incident on Ti-6Al-4V.

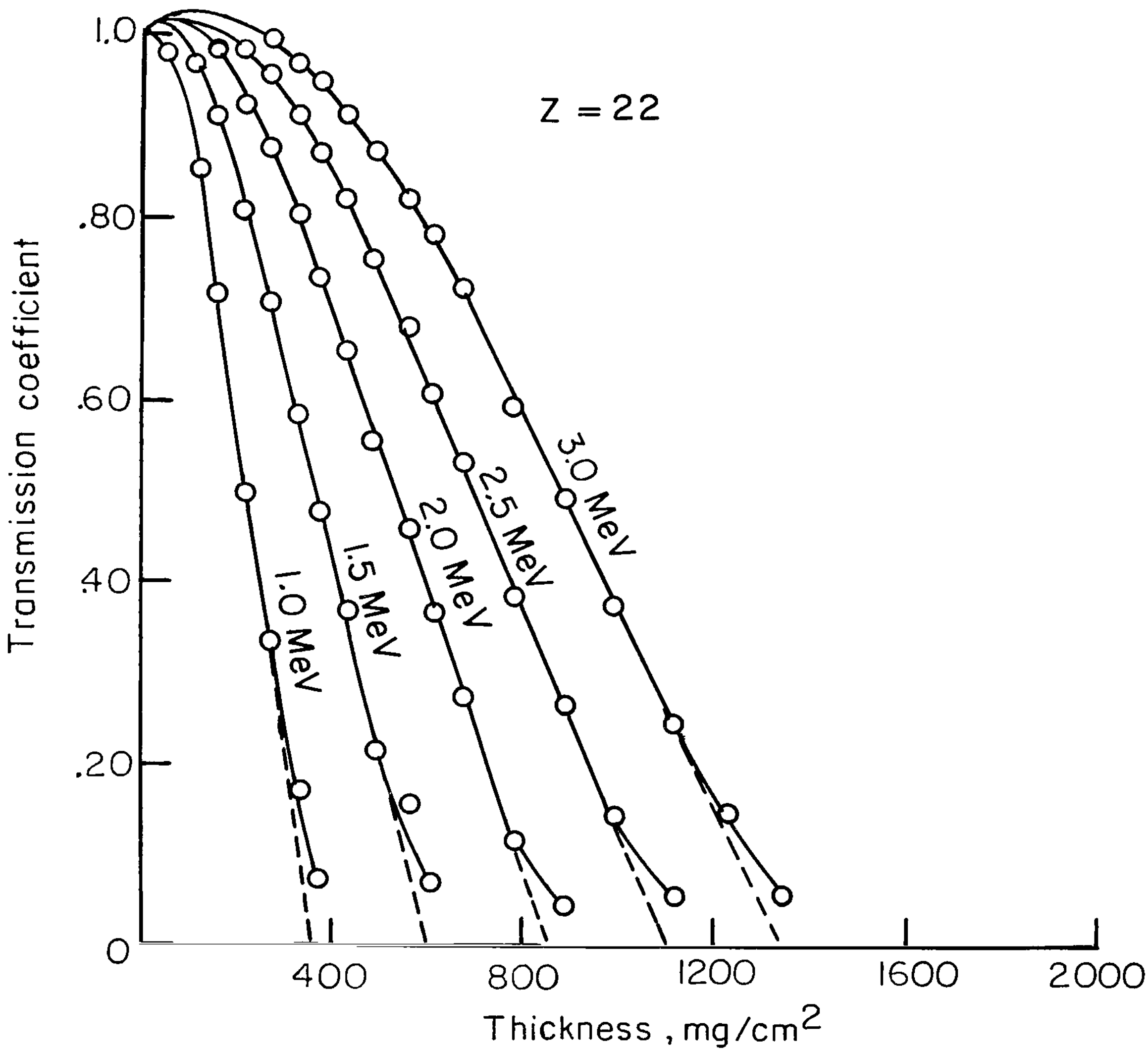

Figure 5.- Transmission coefficients as a function of target thickness for electrons normally incident on titanium.

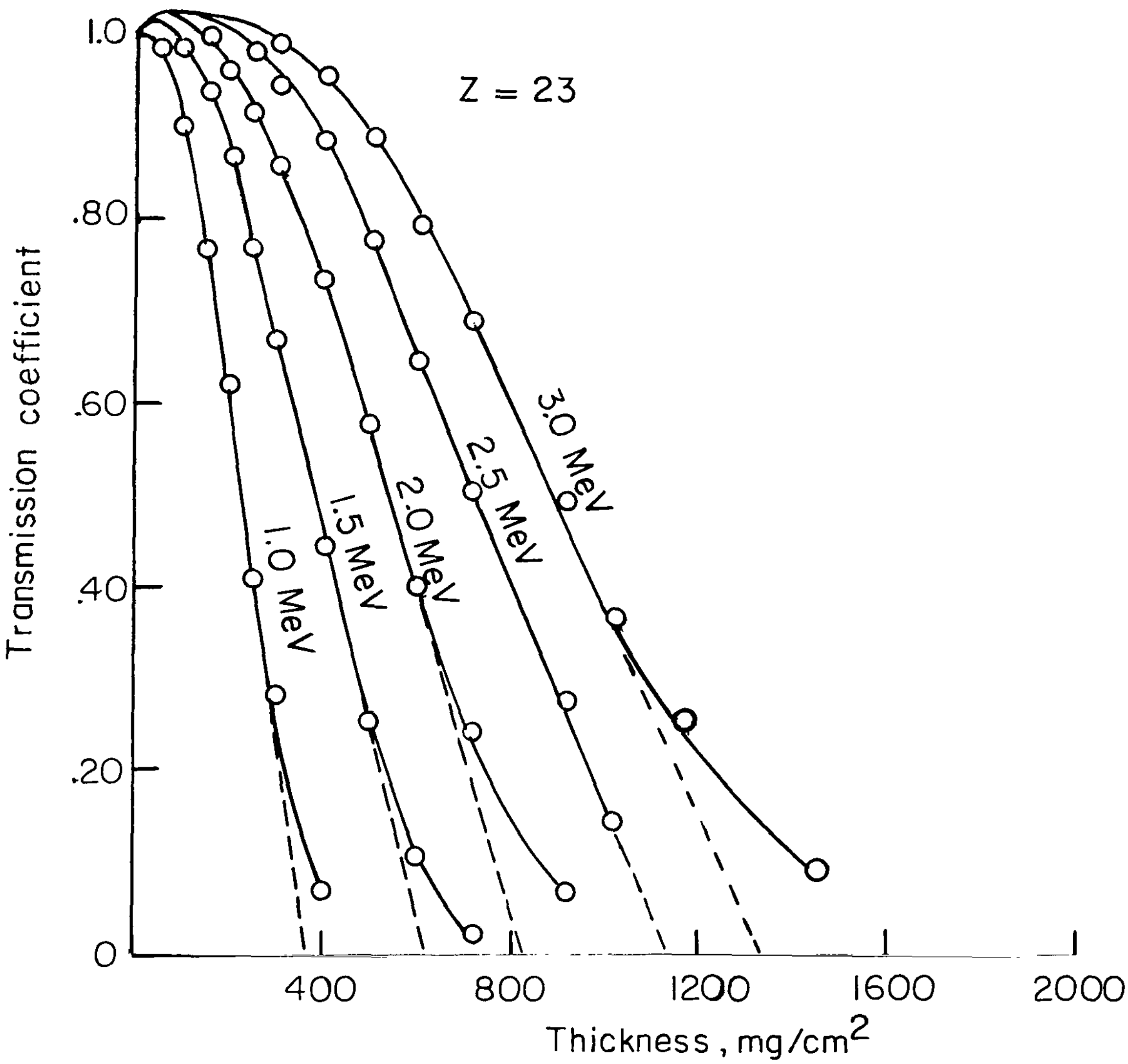

Figure 6.- Transmission coefficients as a function of target thickness for electrons normally incident on vanadium.

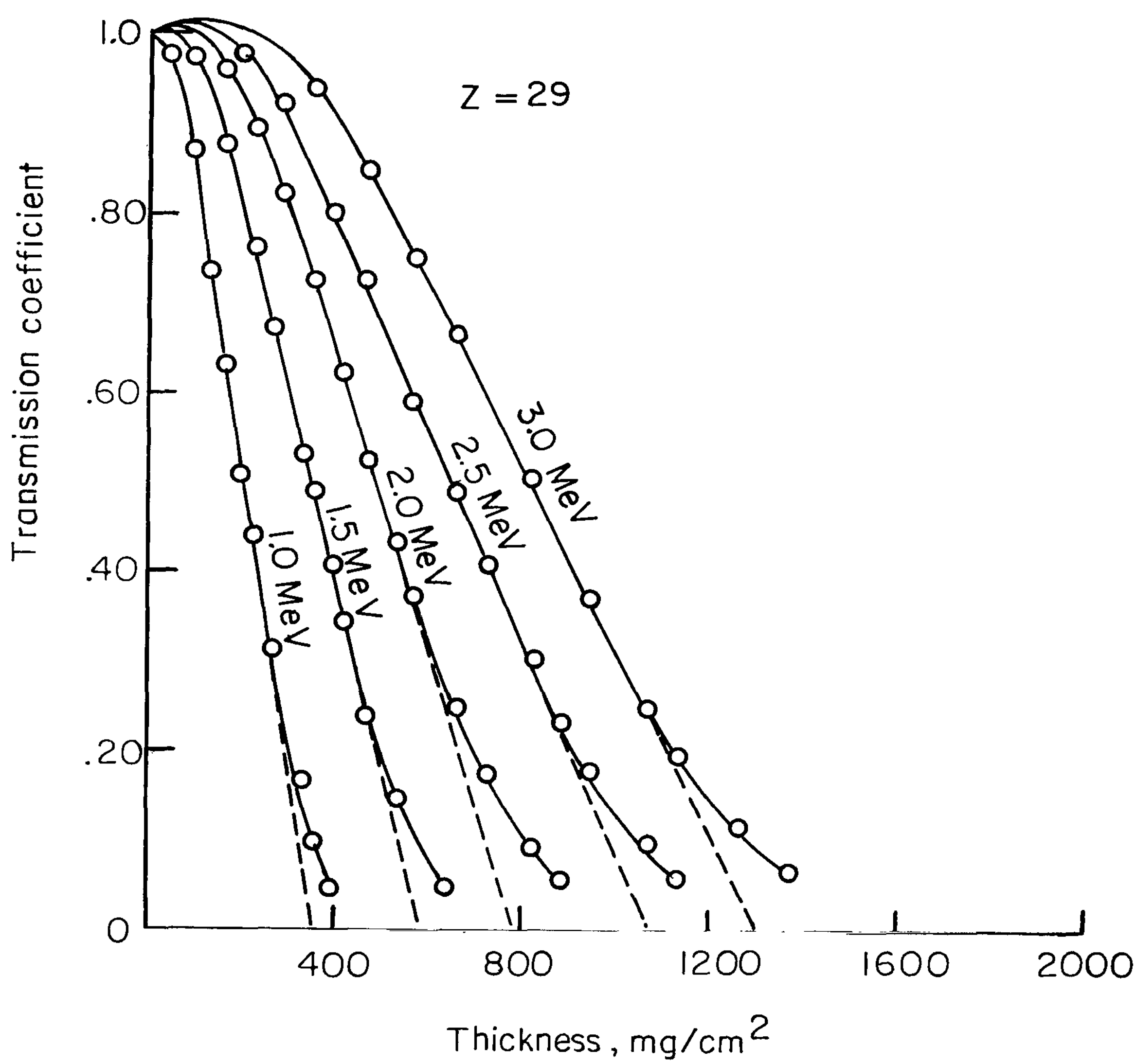

Figure 7.- Transmission coefficients as a function of target thickness for electrons normally incident on copper.

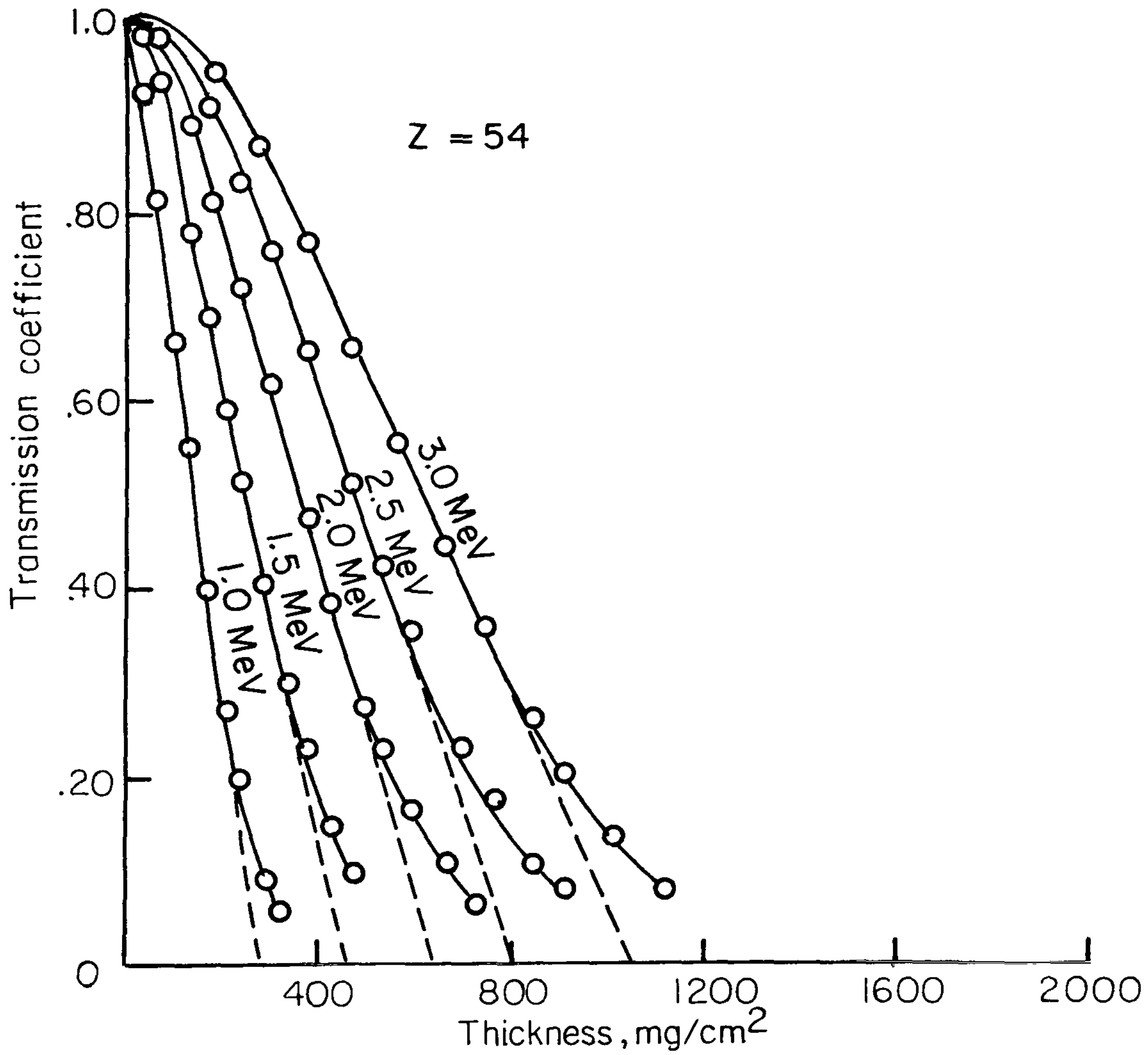

Figure 8.- Transmission coefficients as a function of target thickness for electrons normally incident on 50% Cu – 50% Au.

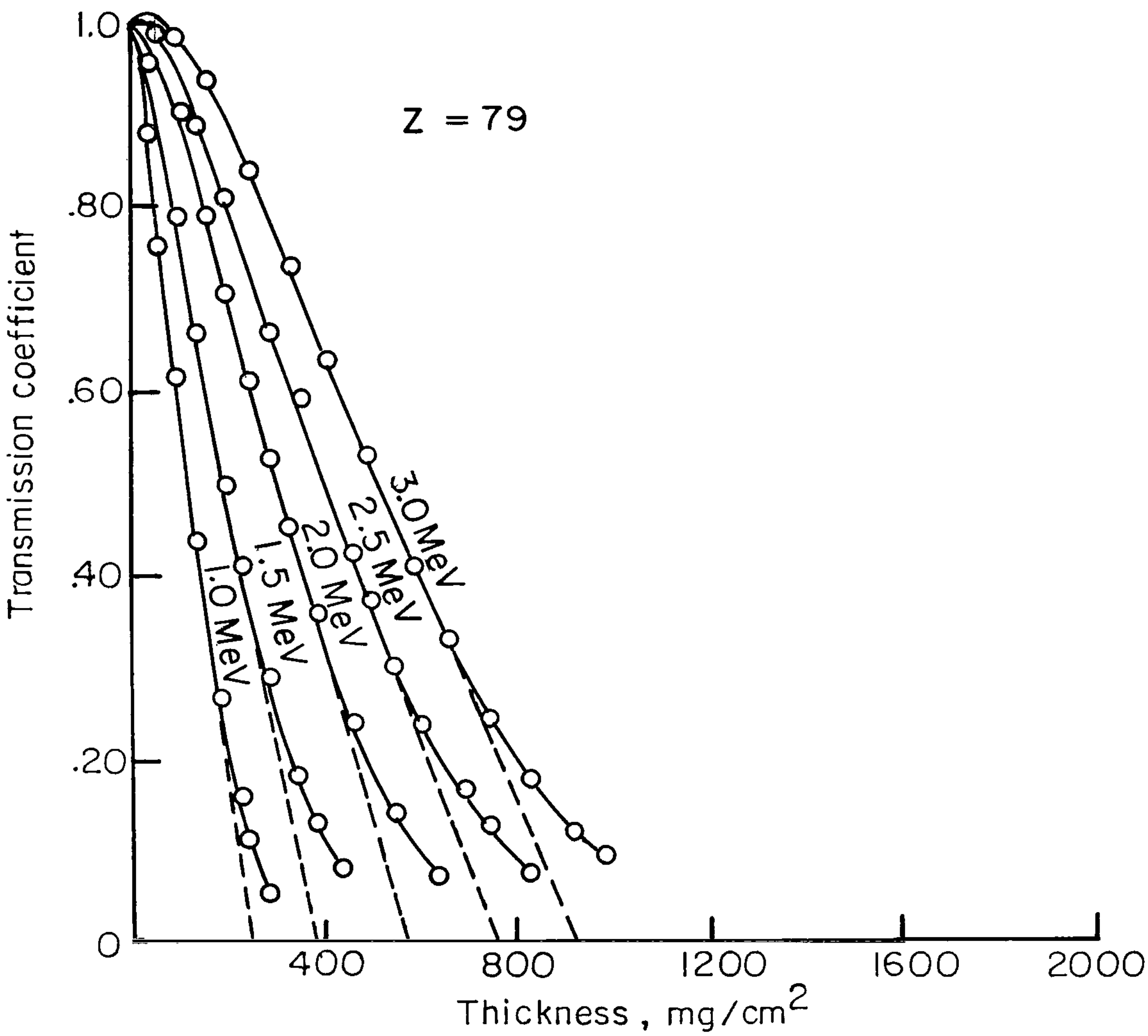

Figure 9.- Transmission coefficients as a function of target thickness for electrons normally incident on gold.

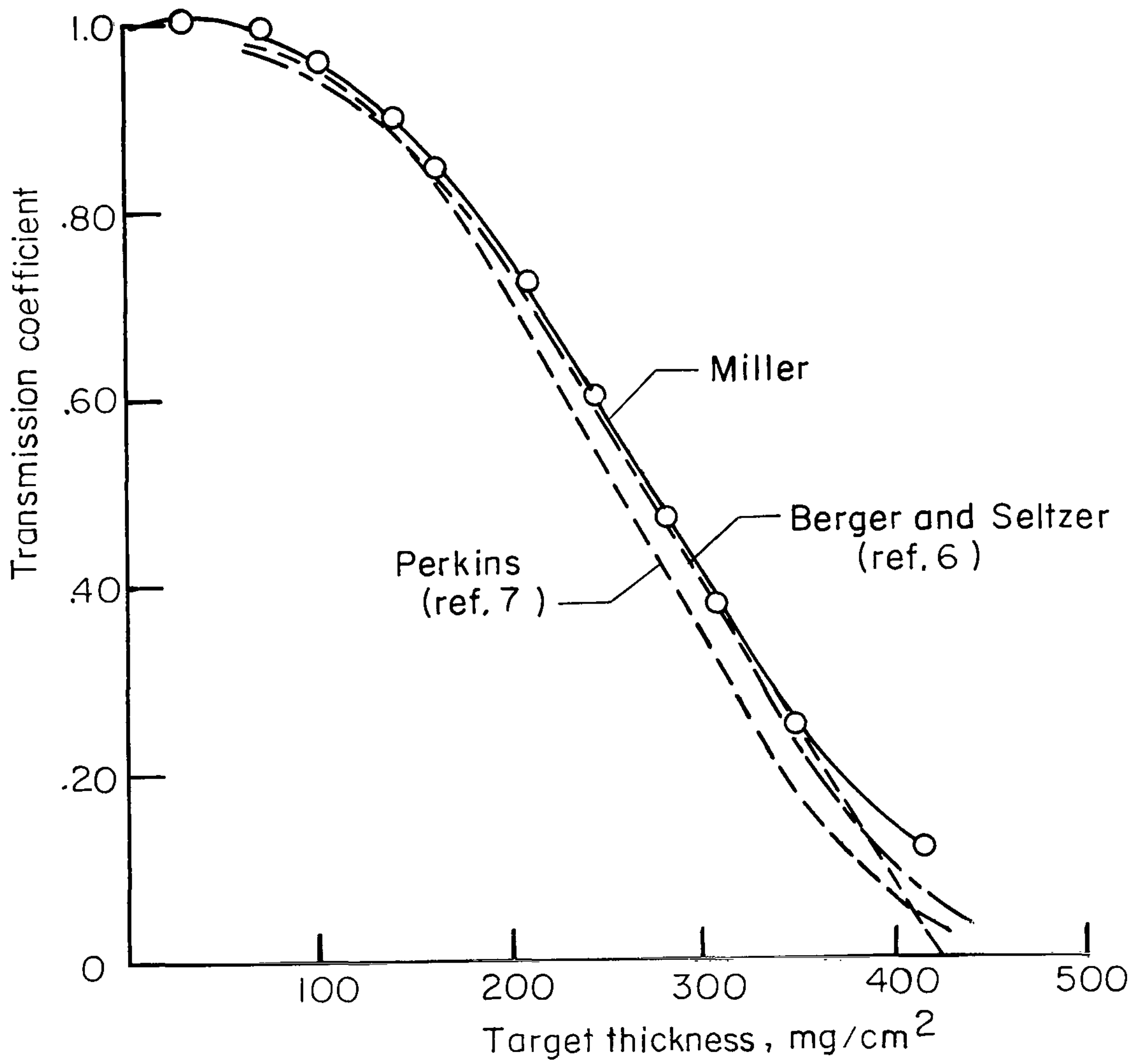

Figure 10.- Comparison of experimental transmission coefficients of this work with theoretical values for 1.0-MeV electrons normally incident on aluminum.

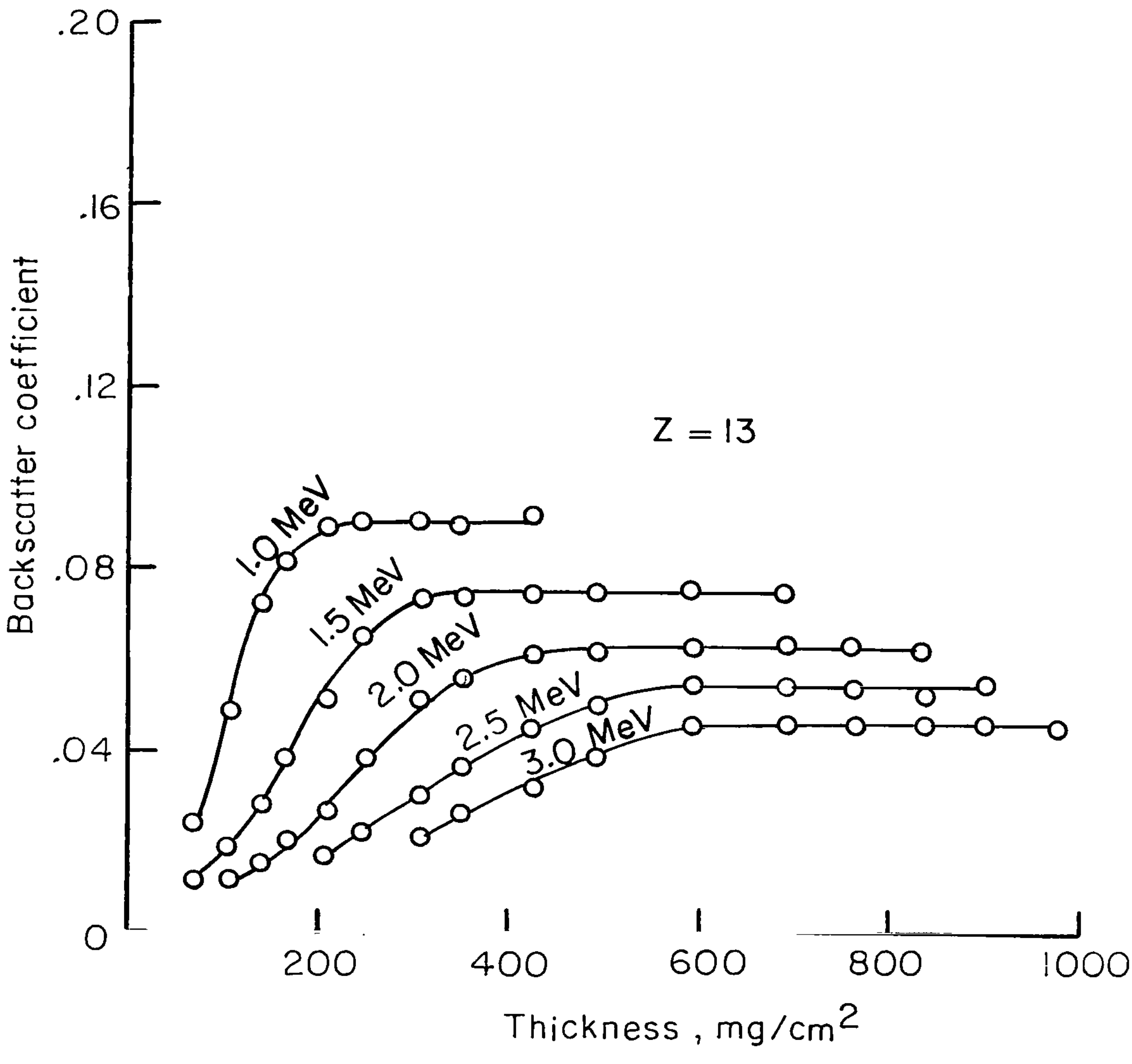

Figure 11.- Backscatter coefficients as a function of target thickness for electrons normally incident on aluminum.

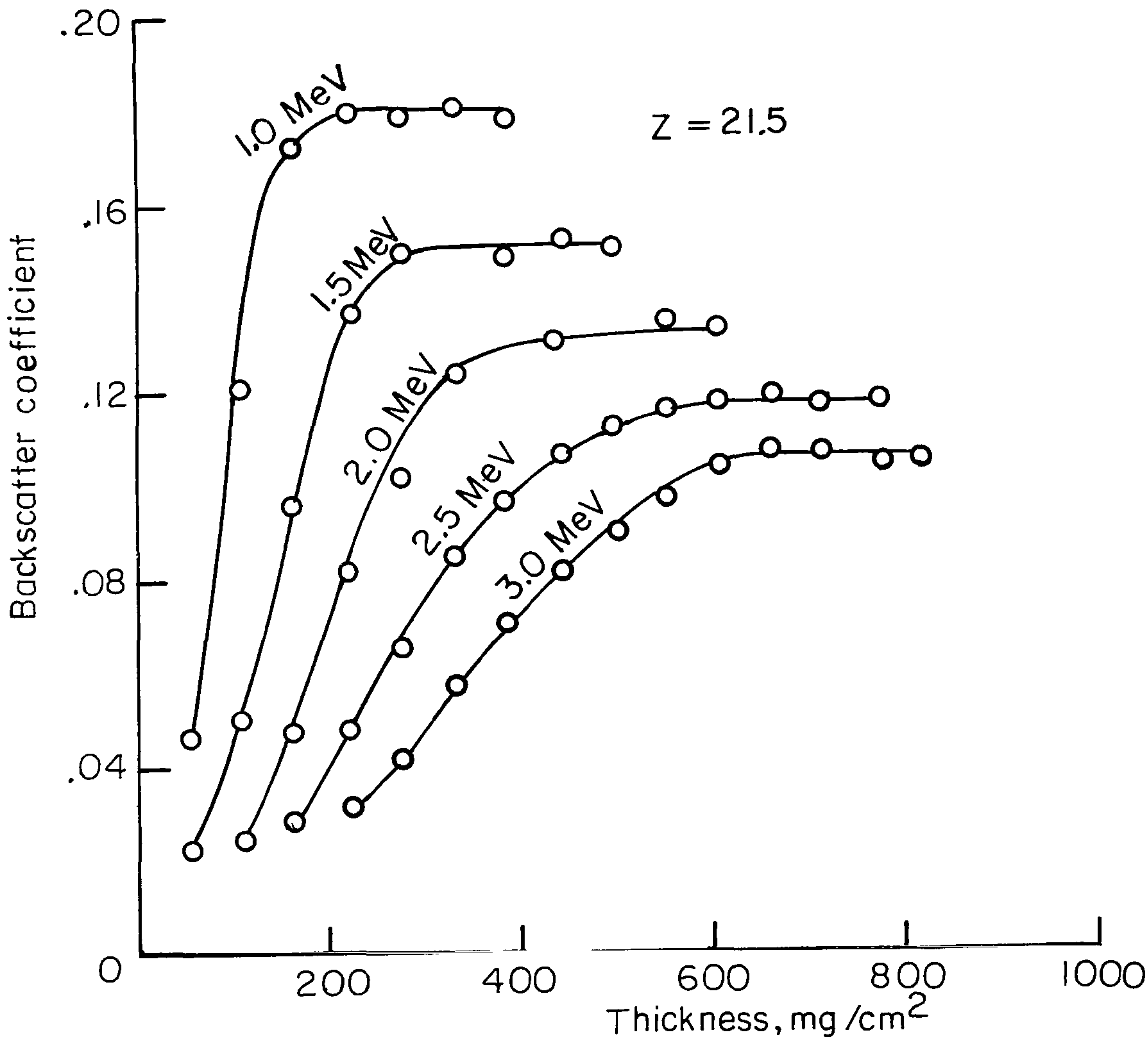

Figure 12.- Backscatter coefficients as a function of target thickness for electrons normally incident on Ti-6Al-4V.

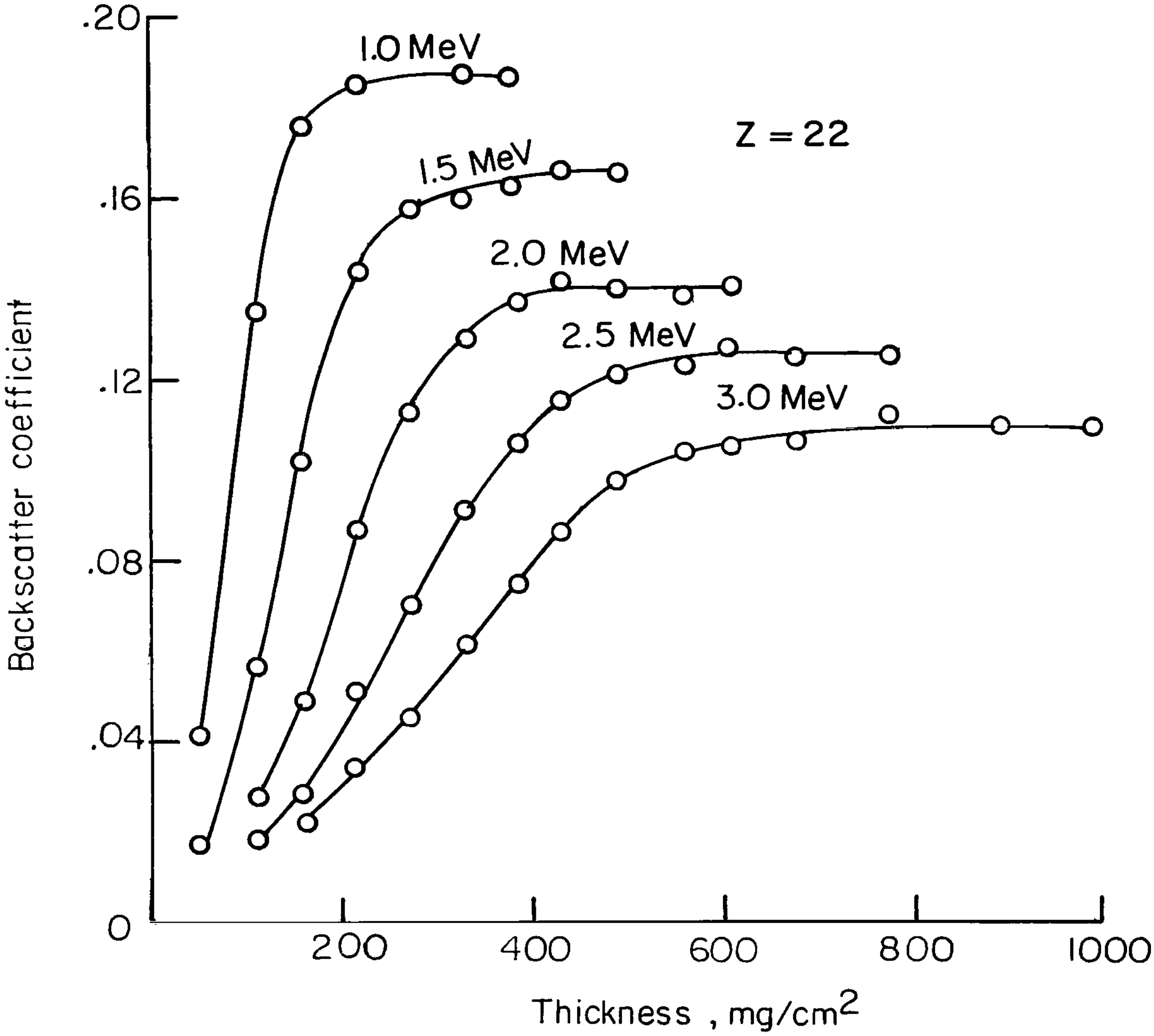

Figure 13.- Backscatter coefficients as a function of target thickness for electrons normally incident on titanium.

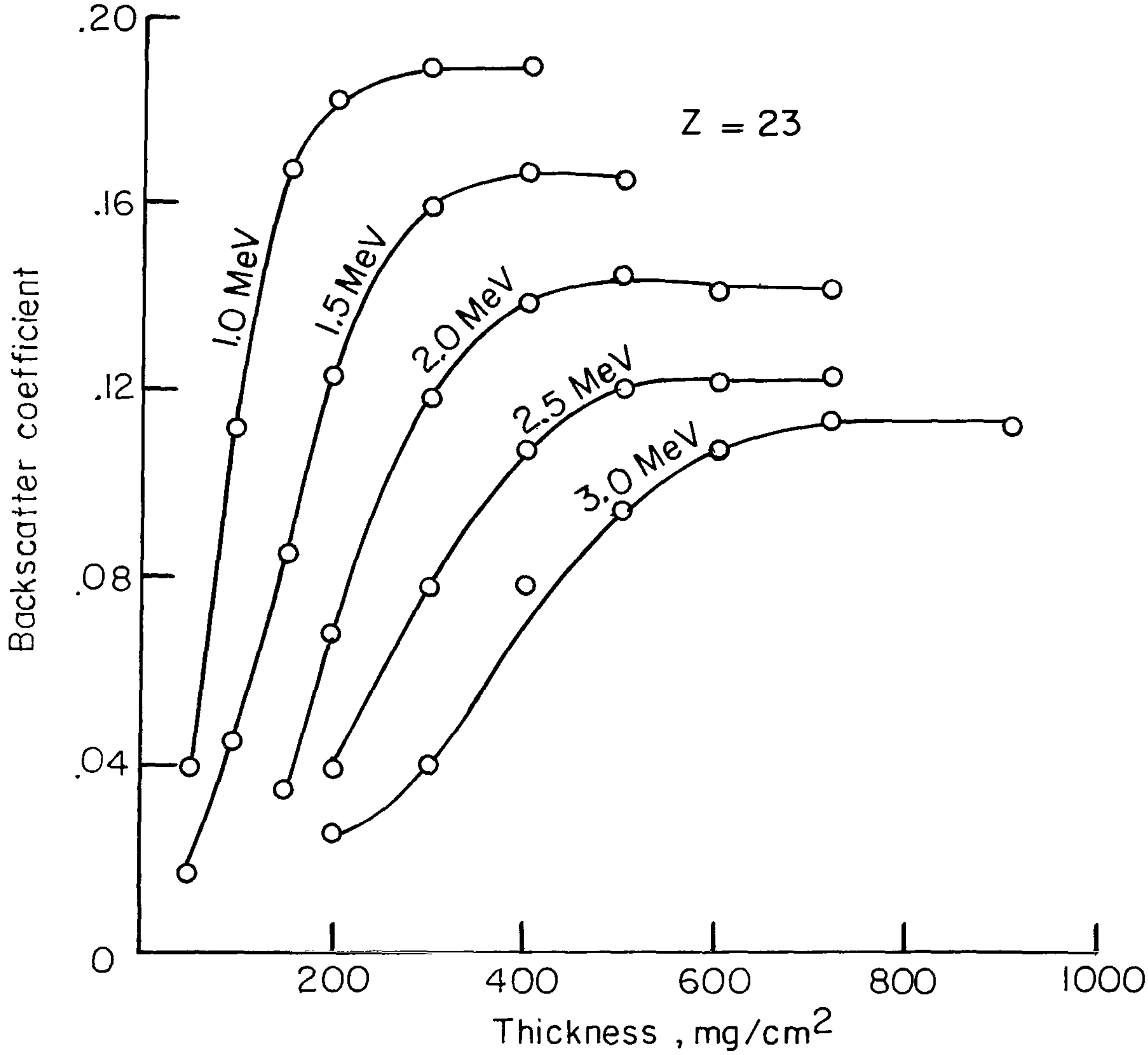

Figure 14.- Backscatter coefficients as a function of target thickness for electrons normally incident on vanadium.

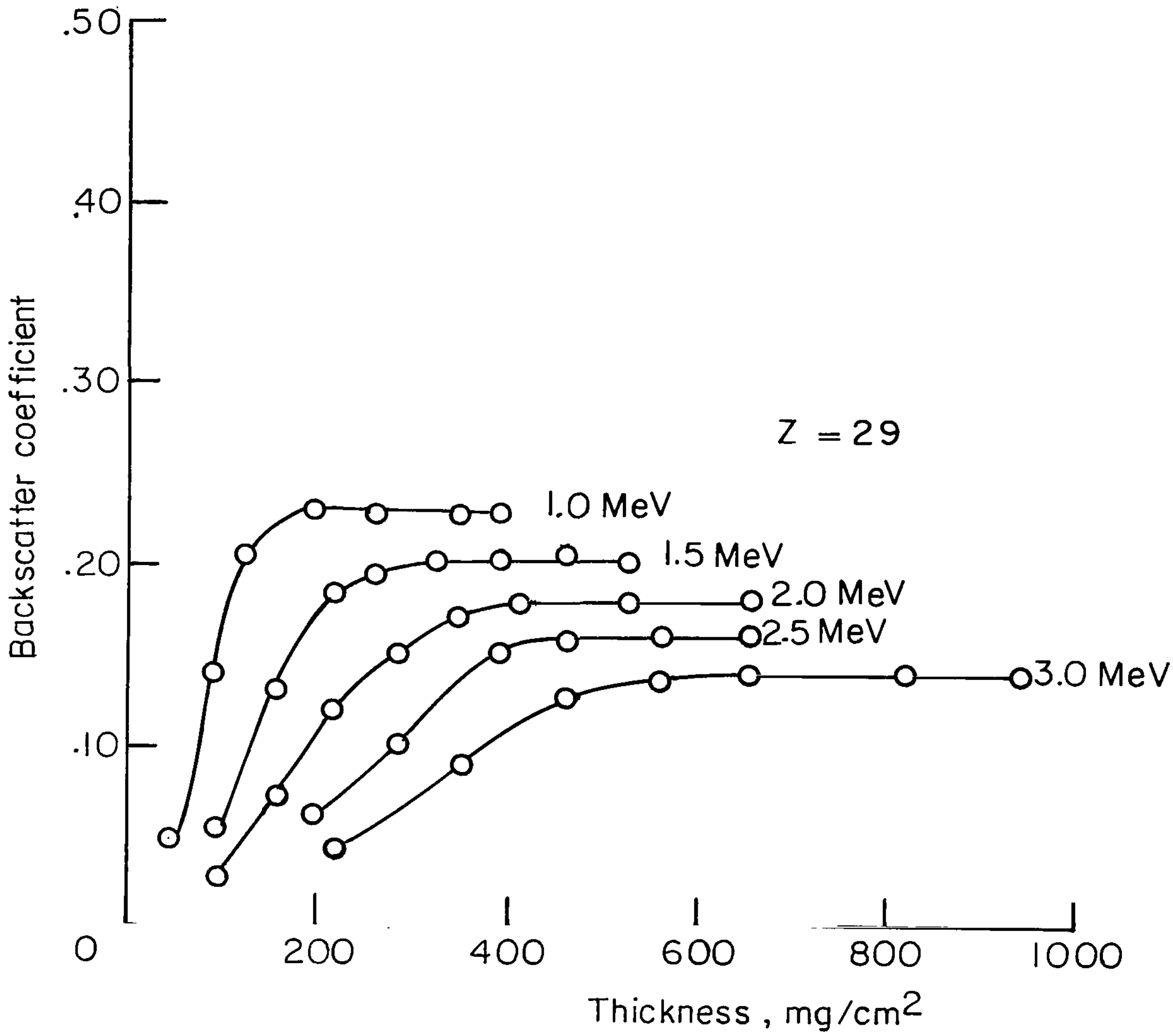

Figure 15.- Backscatter coefficients as a function of target thickness for electrons normally incident on copper.

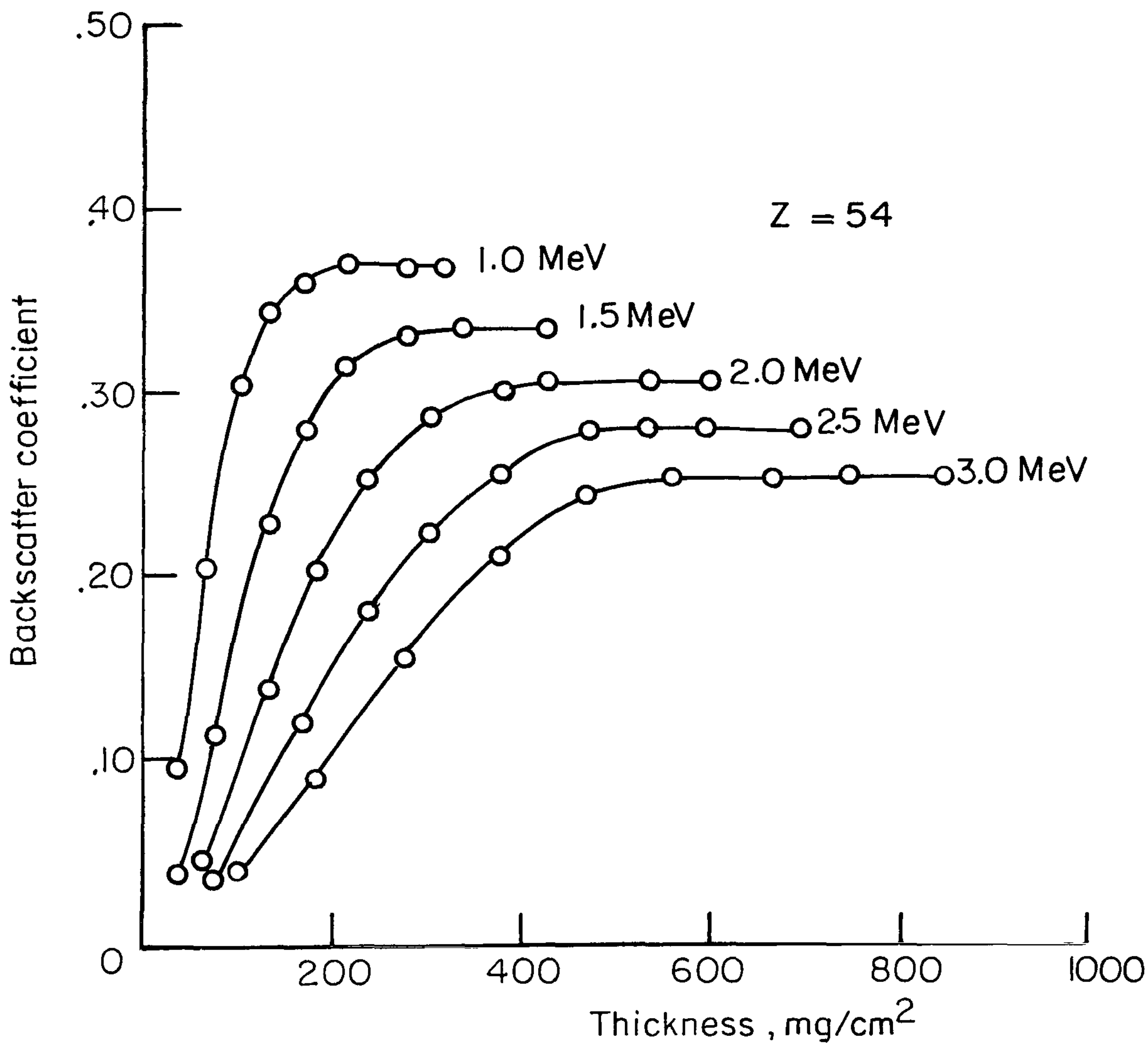

Figure 16.- Backscatter coefficients as a function of target thickness for electrons normally incident on 50% Cu – 50% Au.

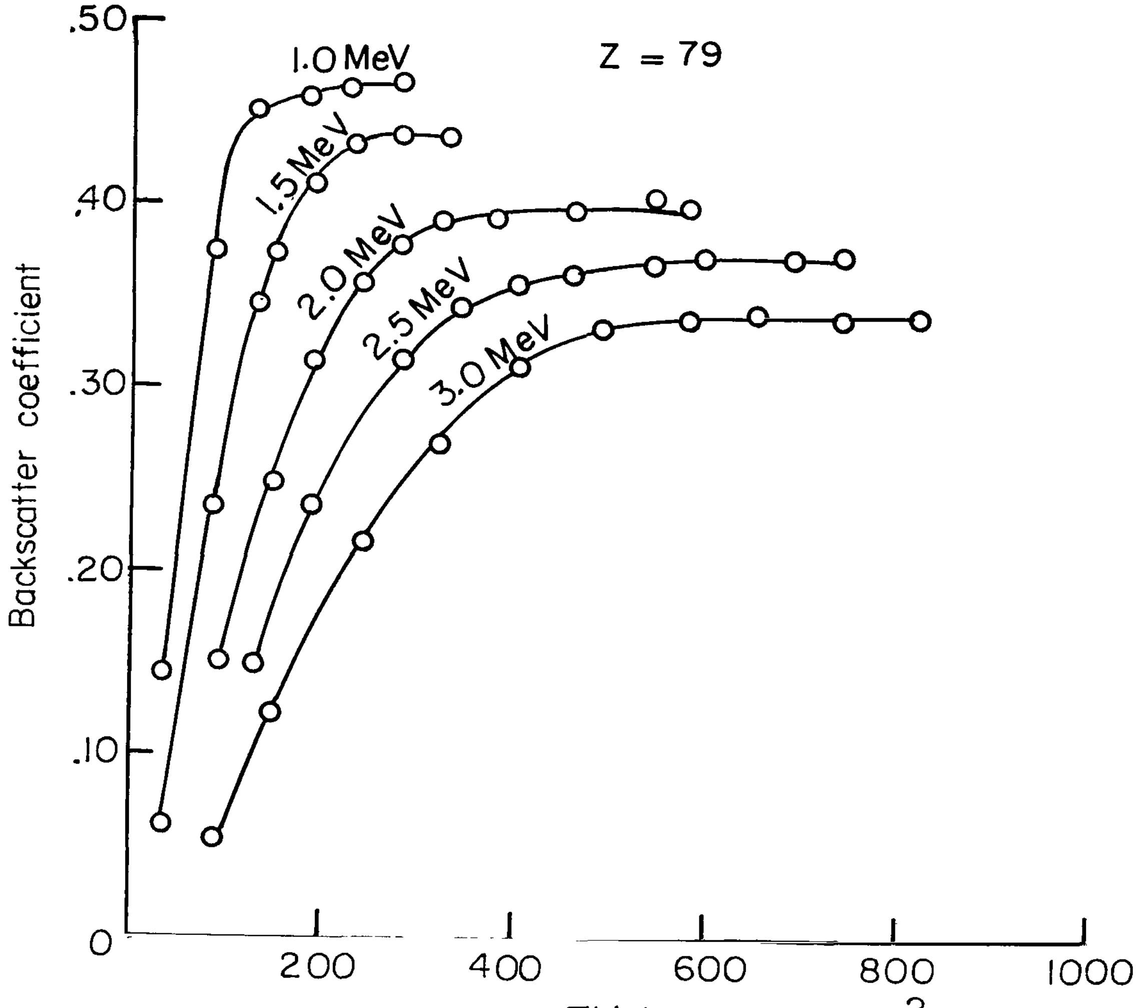

Figure 17.- Backscatter coefficients as a function of target thickness for electrons normally incident on gold.

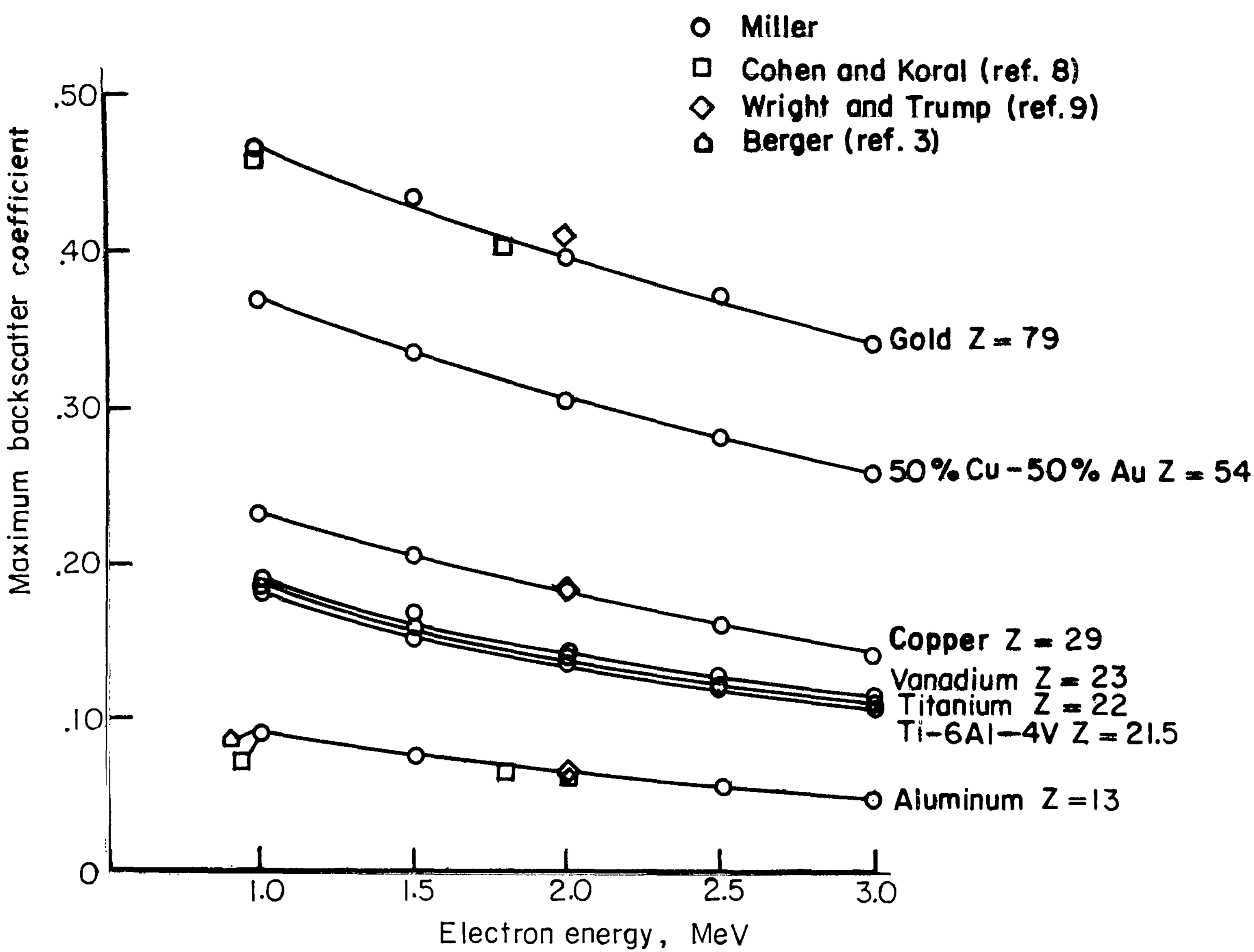

Figure 18.- Comparison of maximum backscatter coefficient with other experiments and theory for normally incident electrons.

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